RADAR SYSTEM

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RADAR SYSTEM

Government Funded Invention

Background of the Invention

1. Field of the Invention

The invention is related to the field of radar systems, and in particular, to radar systems

10   that transfer pulses at a target to determine the range and velocity of the target.

2. Statement of the Problem

A Doppler weather radar system determines the range and velocity of atmospheric

structures, such as wind and precipitation. The Doppler weather radar system transfers pulse

15   trains toward the target structure and receives echoes reflected off of the target structure. The

Doppler weather radar system processes the echoes to determine the range and velocity of the

atmospheric structure. In addition, the Doppler weather radar system determines other variables,

such as differential reflectivity, differential phase, linear depolarization ratio, and co-polar

correlation coefficient.

20   To determine the target range, the radar system determines the time that it takes for a

pulse to propagate to the target and for its echo to propagate back to the radar system. The range

is then determined based on the expected speed of the pulses/echoes and the elapsed time.

However, the echoes from consecutive pulses may be confused by the radar system. For

example, a first pulse may reflect off of the target to provide a first echo, and a second pulse may reflect off of the target to provide a second echo. However, the first pulse may continue to propagate and reflect off of another structure that is further away from the radar system than the target structure to produce a third echo. The third echo may arrive at the receiver around the

5   same time as the second echo. The receiver may confuse the two echoes and provide an ambiguous or inaccurate target range. These confounded echoes are referred to as range overlaid echoes in the literature.

To counter the ambiguous range problem, it is desirable to separate consecutive pulses by a relatively long Pulse Repetition Time (PRT). The longer PRT allows all echoes from the first

10   pulse to clear the radar system before the echoes from the second pulse arrive. This prevents the receiver from confusing the echoes of consecutive pulses.

To determine target velocity, the radar system determines the phase shift that occurs between two echoes returned from a common target, since the velocity of the target affects this phase shift according to the Doppler effect. To get proper phase shift data, the target must be

15   sampled at the Nyquist rate or at a higher rate, and these rates require a shorter PRT to adequately sample for unambiguous target velocity.

The velocity determination can be further complicated by the introduction of phase shift that is not attributed to the velocity of the target structure. For example, additional phase shift is introduced to both the pulse and its echo by the particles that are in between the radar system and

20   the target structure. Since this other phase shift is not the Doppler phase shift of interest, the other phase shift introduces ambiguity into the velocity determination.

Unfortunately, larger unambiguous range determination requires a longer PRT, but larger unambiguous velocity determination requires a shorter PRT. This problem of simultaneously

obtaining larger unambiguous range and larger unambiguous velocity is termed in the literature as the Doppler Dilemma. It is expressed by the following equation:

$$r_a v_a = c\lambda/8;$$

where r_a is the unambiguous range, v_a is the unambiguous velocity, c is the speed of light, and λ

5   is the wavelength of the transmitted radar signal. Various techniques have been tried to simultaneously extend both the unambiguous range and velocity of the target, despite the conflicting pulse repetition requirements.

One technique to handle the range/velocity ambiguity problem is to use dual scans where the first scan has a short PRT for velocity determination, and the second scan has a longer PRT

10   for range determination. Unfortunately, the dual scanning technique may take an undesirable amount of time to perform both scans, and range overlaid echoes can contaminate the short PRT scan.

Another technique to handle the range/velocity ambiguity problem is to alternate the period between the pulses between a short PRT and a long PRT, called a staggered PRT. The

15   unambiguous velocity can be extended to an equivalent uniform PRT of the difference of the long and short PRT periods, while the unambiguous range can be extended to an equivalent uniform PRT of the sum of the long and short PRT. Unfortunately, complex filters are required to remove noise caused by ground clutter when the PRT is alternated.

Another technique to mitigate range-velocity ambiguity is to use systematic phase coding

20   of the transmitted pulses. In this way, the various range overlaid echoes can be separated using the phase code information. This technique works well for two overlaid echoes, but becomes very difficult when three or more echoes are overlaid.

Another technique to handle the range/velocity ambiguity problem is to transfer a first

pulse train at a first polarity and with a set pulse repetition time, and to transfer a second pulse

train at a second polarity, but with an alternating PRT. The alternating PRT means that, for the

second pulse train, a first pulse is transmitted slightly before a corresponding first pulse in the

5   first pulse train, and a second pulse is transmitted slightly after a corresponding second pulse in

the first pulse train. Thus, pulses in the second pulse train alternate between transmission

slightly before or after pulses in the first pulse train. Unfortunately, the continually alternating

PRT adds undesired complexity to ground clutter filtering and to phase coding.

10   **Summary of the Solution**

Examples of the invention include a radar system and its method of operation. The radar

system comprises a transmission system and a reception system. The transmission system is

configured to transfer a first series of pulses and a second series of pulses. The first series of

pulses and the second series of pulses have orthogonal polarizations. The first series of pulses

15   and the second series of pulses have a same pulse repetition time. The first series of pulses and

the second series of pulses are offset by a time amount. A target reflects energy from the first

series of pulses to generate a first series of echoes. The target reflects energy from the second

series of pulses to generate a second series of echoes. The reception system is configured to

process the first series of echoes and the second series of echoes to determine a range and a

20   velocity of the target.

In some example of the invention, the first series of pulses and the second series of pulses

each comprise blocks of the pulses, and the transmission system is configured to alternate the

blocks from the first series of pulses between a lead position and a lag position with respect to the blocks from the second series of pulses.

In some example of the invention, the transmission system is configured to phase code the first series of pulses and the second series of pulses, and the reception system is configured to

5 decode the phase coding to distinguish ones in the first series of echoes from adjacent ones in the second series of echoes.

In some example of the invention, the orthogonal polarizations are substantially parallel and perpendicular to earth's surface.

In some example of the invention, the reception system is configured to co-process ones

10 in the first series of echoes with adjacent ones in the second series of echoes to determine the velocity of the target.

In some example of the invention, the reception system is configured to co-process adjacent ones in the first series of echoes and co-process adjacent ones in the second series of echoes to determine the range of the target.

15 In some example of the invention, the pulse repetition time is in a range from one-half millisecond to four milliseconds.

In some example of the invention, the time amount is in a range from one microsecond to 300 microseconds.

In some example of the invention, the target comprises an atmospheric structure.

20 In some example of the invention, the radar system comprises a Doppler weather radar system.

Description of the Drawings

The same reference number represents the same element on all drawings.

FIG. 1 illustrates a radar system in an example of the invention.

FIG. 2 illustrates a first and second series of pulses in an example of the invention.

5 FIG. 3 illustrates a first and second series of pulses in an example of the invention.

FIG. 4 illustrates radar system processing in an example of the invention.

Detailed Description of the Invention

FIGS. 1-4 and the following description depict a specific example to teach those skilled

10 in the art how to make and use the best mode of the invention. For the purpose of teaching

inventive principles, some conventional aspects have been simplified or omitted. Those skilled

in the art will appreciate variations from this example that fall within the scope of the invention.

Those skilled in the art will appreciate that the features described below can be combined in

various ways to form multiple variations of the invention. As a result, the invention is not

15 limited to the specific example described below, but only by the claims and their equivalents.

FIG. 1 illustrates radar system 100 in an example of the invention. Radar system 100

determines the range and velocity of target 105. Target 105 could be an atmospheric structure,

such as wind or precipitation. Radar system 100 could be a Doppler weather radar system, Lidar

system, or other radar-like system.

20 Radar system 100 includes transmission system 101 and reception system 102.

Transmission system 101 receives control signal 103. Transmission system 101 transfers a first

series of pulses 111 and a second series of pulses 121 toward target 105. Target 105 reflects

energy from first series of pulses 111 to generate first series of echoes 112. Target 105 reflects

energy from second series of pulses 121 to generate second series of echoes 122. Reception system 102 receives and processes first series of echoes 112 and second series of echoes 122 to determine the range and velocity of target 105. Reception system 102 provides output signal 104 that indicates the range and velocity of target 105.

5   Other variables may also be determined by processing the echoes, such as the differential reflectivity, differential phase, linear de-polarization ratio, and co-polar correlation coefficient. The differential reflectivity is the co-polar power differential between echoes 112 and 122. The differential phase is the co-polar phase differential between echoes 112 and 122. The linear de-polarization ratio is a ratio of the cross-polar power to the co-polar power. The co-polar

10   correlation coefficient indicates the degree of similarity between echoes 112 and 122.

FIG. 2 illustrates first series of pulses 111 and second series of pulses 121 in an example of the invention. On FIG. 2, the horizontal axis represents time and the vertical axis represents magnitude and polarity. First series of pulses 111 includes pulses 211-214. Second series of pulses 121 includes pulses 221-224. First series of pulses 111 and second series of pulses 121

15   both have the same pulse repetition time T_P. First series of pulses 111 and second series of pulses 121 are offset from one another by an offset time amount T_O, where the first series of pulses 111 leads the second series of pulses 121 by the offset time amount T_O.

In some examples, the pulse repetition time T_P is in a range from one-half millisecond to four milliseconds, and the time amount T_O is in a range from one microsecond to 300

20   microseconds. In addition, control signal 103 may specify new values for T_O and T_P, and in response, transmission system 101 would change the prior values of T_O and T_P to the newly specified values for the transmission of pulse series 111 and 121.

First series of pulses 111 and second series of pulses 121 have orthogonal polarizations. On FIG. 2, the pulses above the time axis have a first polarization, and the pulses below the time axis have a second polarization – where the first polarization is orthogonal to the second polarization. For example, the polarization of pulse 211 is orthogonal to the polarization of pulse

5   221. In some examples, one of the orthogonal polarizations is substantially perpendicular to the earth's surface, and the other one of the orthogonal polarizations is substantially parallel to the earth's surface. These perpendicular and parallel polarizations are respectively referred to as horizontal and vertical polarizations.

     To determine the range of target 105, reception system 102 co-processes adjacent echoes

10   from first series of echoes 112 and co-processes adjacent echoes from second series of echoes 122. For example, reception system 102 would co-process echoes for adjacent pulses 211 and 212 in first series of echoes 111, and co-process echoes for adjacent pulses 221 and 222 in second series of echoes 122. The term "co-process" means that data from the echoes are used in the same equations at the same time.

15   Advantageously, the relatively long time T_P between the adjacent pulses of the same series provides a relatively slow sampling rate to unambiguously determine the target range. The slow sampling rate allows echoes from the prior pulse to clear before echoes from the next pulse in the same series are received. Thus, reception system 102 is unlikely to confuse echoes from adjacent pulses in the same series.

20   To determine the velocity of target 105, reception system 102 co-processes adjacent echoes from first series of echoes 112 and second series of echoes 122. For example, reception system 102 would co-process echoes for adjacent pulses 211 and 221 and co-process echoes for adjacent pulses 212 and 222.

Advantageously, the relatively short time amount T_O between the adjacent pulses of the different series provides a relatively fast sampling rate to unambiguously determine the target velocity. The fast sampling rate can handle the Doppler frequency shifts of high velocity targets.

Reception system 102 must also distinguish between echoes from the adjacent pulses of the different series where the separation between the adjacent pulses is the short time amount T_O. For example, echoes from pulses 211 and 221 must be distinguished. The different polarities of the pulses from the different series can be used to distinguish their respective echoes. To handle cross-polar interference between these pulses, transmission system 101 phase codes first series of pulses 111 differently from second series of pulses 121. Reception system 102 decodes this phase coding to distinguish first series of echoes 112 from second series of echoes 122. For example, reception system 102 uses the phase coding to distinguish the echoes from adjacent pulses 211 and 221, or to distinguish the echoes from adjacent pulses 212 and 222.

FIG. 3 illustrates first series of pulses 111 and second series of pulses 121 in an example of the invention. FIG. 3 is a continuation of FIG. 2, starting with pulses 214 and 224 that appear on both FIGS. 2-3. The second series of pulses 121 continues to use the standard pulse repetition time T_P, so pulse 225 follows pulse 224 by T_P, and pulse 226 follows pulse 225 by T_P. However in the first series of pulses 111, pulse 215 does not follow pulse 214 by the standard pulse repetition time T_P, but instead, is delayed by an additional $2T_O$. Starting with pulse 216 (which follows delayed pulse 215), the first series of pulses 111 again uses the standard pulse repetition time T_P. Note that until pulses 214 and 224, the first series of pulses 111 led the second series of pulses 121 by the time offset T_O, but after pulses 214 and 224, the first series of pulses 111 lags the second series of pulses 121 by the time offset T_O. After a set number of pulse pairs (two pulses of different series that are offset by the time amount T_O), the above-described pulse delay

process will occur for the second series of pulses 121, so that the first series of pulses 111 will again lead the second series of pulses by the offset time T_O. This process repeats, so that the first series of pulses 111 and the second series of pulses alternate between leading and lagging one another by the offset time T_O.

5   The lead/lag positioning alternates after a number of pulse pairs, where the number could be in a range of 16-256 or 32-128. Control signal 103 may specify the number of pulse pairs that occur between lead/lag alternation, and in response, transmission system 101 would change the prior number of pulse pairs to the newly specified number of pulse pairs for the transmission of pulse series 111 and 121.

10   The first series and second series of pulses can each be viewed as blocks of consecutive pulses, such as blocks of 64 pulses. For the first block from each series, the block for the first series leads the block for the second series by the offset time T_O. For the second block from each series, the block for the second series leads the block for the first series by the offset time T_O. For the third block from each series, the block for the first series leads the block for the second series 15   by the offset time T_O. This process repeats, so that consecutive blocks from the same series alternate between the lead and lag position with respect to the blocks of the other series.

Advantageously, alternating the lead/lag positioning of the two series of pulses allows reception system 102 to separate phase shift attributed to the velocity of the target structure (the Doppler phase shift) from other phase shift, such as the other phase shift that is introduced by 20   particles in between the radar system and the target structure. Alternating the lead/lag positioning changes the sign of the Doppler phase shift while leaving the sign of the other phase shift alone, and thus, the Doppler phase shift may be mathematically separated from the other

phase shift. The ability to separate the Doppler phase shift from the other phase shift improves the accuracy of the velocity determination.

Even though the lead position alternates between the two pulse series, note that the pulse repetition time T_P for the pulses in both series largely remains the same. Only a single pulse is periodically delayed to alternate the lead position between the two series. Advantageously, the consistent pulse repetition time simplifies ground clutter filtering and phase coding. In contrast, ground clutter filtering and phase coding are relatively complex if the pulse repetition time is allowed to alternate on a pulse-by-pulse basis as is done in some prior systems.

FIG. 4 and the following section describe the processing that is used by Radar system 100 in one example of the invention to determine the range and velocity of the target, in addition to other variables. Note that other processing variations could be used in other examples of the invention.

1. Staggered H and V Pulse Trains

1.1 Estimation of copolar and crosspolar signals via phase coding

First the copolar and crosspolar components of the received horizontal and vertical

5   voltages are estimated via phase coding. Refer to Figure 4. At time t_s the received voltages are:

$$
\begin{aligned}
H^{(1)}(i) &= hh^{(1)}(i, t_s)\exp\{j\phi_i\} + hv^{(1)}(i, t_s - t_1)\exp\{j\psi_i\} & (1) \\
V^{(1)}(i) &= vv^{(1)}(i, t_s)\exp\{j\psi_i\} + vh^{(1)}(i, t_s + t_1)\exp\{j\phi_i\} & (2) \\
H^{(2)}(i) &= hh^{(2)}(i, t_s)\exp\{j\phi_i\} + hv^{(2)}(i, t_s + t_1)\exp\{j\psi_i\} & (3) \\
V^{(2)}(i) &= vv^{(2)}(i, t_s)\exp\{j\psi_i\} + vh^{(2)}(i, t_s - t_1)\exp\{j\phi_i\} & (4)
\end{aligned}
$$

10

where H and V are the received voltages for the horizontal and vertical polarizations,

respectively, and where the letter pairs refer to the received and transmitted polarizations. For

example, vh is transmit horizontal polarization receive vertical polarization. $\emptyset_i$ and ψ_i are the

phase codes applied to the horizontal and vertical transmitted pulses respectively. The letter i

15   represents the time series index for the radar copolar resolution volume defined at time t_s, and j is

the square root of -1. The superscript (1) refers to the samples obtained when the V pulses lag

the horizontal pulses by t_1. The superscript (2) refers to the samples obtained when the vertical

pulses lead the horizontal pulses by t_1. In the equations below, it is assumed that $t_1 < t_s < T - t_1$;

however, the processing principles are identical.

20   Before processing the samples to retrieve the desired radar measurables, the copolar and

cross polar time series first need to be estimated. Note that in prior systems (Sachidananda and

Zrnić), the objective was to estimate only the radar moments of power, velocity and spectrum

width. Here we need to obtain the copolar time series so that differential phase, velocity and

copolar correlation coefficient can be estimated. The phase codes should be chosen so that overlaid echoes have a unique phase code. For example, if the sequence length is 64 and the SZ(8/64) phase code is chosen, then a good choice is $\psi_i = \phi_{i-3}$.

5   It is possible that second trip echoes may overlay the received voltages given in equations 1, 2, 3 and 4. Under certain conditions, it is possible to separate three or more overlaid signals but in the following discussion it is assumed that only first trip echoes are present, i.e., all significant targets lie within the range $cT/2$ where c is the velocity of light and T is the pulse repetition time.

     Recovery of the weaker echo for overlaid SZ phase coded signals consists of the

10   following steps:

1. Cohere to the stronger signal.

2. Apply an aggressive window function to the resulting time series such as the Hanning window.

15   3. Apply a Fast Fourier Transform (FFT) to obtain the frequency spectrum.

4. Notch out the strong signal spectrum.

5. Inverse Fast Fourier Transform (IFFT) resulting spectrum.

6. Cohere to the weak signal.

20   The time series for the strong and weak signal components of the horizontal received signal are designated S_H and W_H, respectively, while the time series for the strong and weak signal components of the vertical received signal are designated S_V and W_V, respectively. These time series may be either copolar or crosspolar.

The strong signal is estimated as:

$$S_H^{(1)}(i, t_s) = H^{(1)}(i, t_s) \tag{5}$$
$$S_V^{(1)}(i, t_s) = V^{(1)}(i, t_s) \tag{6}$$

or

5

$$S_H^{(2)}(i, t_s) = H^{(2)}(i, t_s) \tag{7}$$
$$S_V^{(2)}(i, t_s) = V^{(2)}(i, t_s) \tag{8}$$

The weak signal time series is recovered via the phase coding recovery algorithm outlined above. After the above processing, time series representing the copolar and crosspolar received signal for both the horizontal and vertical receive channel are available at all times, t_s.

10 The recovered horizontal copolar and crosspolar time series are now designated as, $\widehat{H}^{(1)}(i, t_s)$, $\widehat{HV}^{(1)}(i, t_s)$, respectively, and the recovered vertical copolar and crosspolar time series are now designated as, $\widehat{V}^{(1)}(i, t_s)$, $\widehat{VH}^{(1)}(i, t_s)$, respectively. For the second block of pulses, the superscript (2) replaces the superscript (1).

15 1.2 Calculating the radar variables

The processing steps for the proposed pulsing scheme are:

1. Separate the copolar and cross polar time series, as outlined above.

2. Calculate the copolar powers P_h, P_v and crosspolar powers, P_{vh}, P_{hv} for time t_s as:

$$P_h \;=\; \frac{1}{2N}\sum_{i=1}^{N} \hat{H}_i^{(1)} + \hat{H}_i^{(2)} \tag{9}$$

$$P_v \;=\; \frac{1}{2N}\sum_{i=1}^{N} \hat{V}_i^{(1)} + \hat{V}_i^{(2)} \tag{10}$$

$$P_{xh} \;=\; \frac{1}{2N}\sum_{i=1}^{N} \widehat{VH}_i^{(1)} + \widehat{VH}_i^{(2)} \tag{11}$$

$$P_{xv} \;=\; \frac{1}{2N}\sum_{i=1}^{N} \widehat{HV}_i^{(1)} + \widehat{HV}_i^{(2)} \tag{12}$$

3. Correct the strong signal power by subtracting the weak signal power if $10 \log P_s/P_w <$ 20 dB where P_s, P_w are the strong and weak signal powers.

4. Calculate Z_{dr} (copolar differential reflectivity) and LDR_h (linear depolarization ratio for horizontal transmit polarization) as:

$$Z_{dr} \;=\; \frac{P_h}{P_v} \tag{13}$$

$$LDR \;=\; \frac{P_{xh}}{P_h} \tag{14}$$

5. Calculate the copolar differential phase and velocity phase:

$$\theta_1 \;=\; \phi_{dp} - \phi_{vel} = \arctan \sum_{i=1}^{N} \hat{V}_i^{(1)} \hat{H}_i^{*(1)} \tag{15}$$

$$\theta_2 \;=\; \phi_{dp} + \phi_{vel} = \arctan \sum_{i=1}^{N} \hat{V}_i^{(2)} \hat{H}_i^{*(2)} \tag{16}$$

$$\phi_{vel} \;=\; (\theta_2 - \theta_1)/2 \tag{17}$$

$$\phi_{dp} \;=\; (\theta_2 + \theta_1)/2 \tag{18}$$

where * represents complex conjugation.

6. If t_1 is short, the standard deviation of this above velocity phase estimate, $\emptyset_{vel}$, can be high, but the associated Nyquist folding velocity will be high as compared to the Nyquist folding velocity associated with the time interval T. Thus, velocity phase is also calculated using the first lag autocovariance of the copolar vertical polarized samples as,

$$\phi_{vel\_T} = \arctan \left\{ \left[\sum_{i=1}^{N-1} \hat{V}_i^{(1)} \hat{V}_{i+1}^{*(1)} \right] + \left[\sum_{i=1}^{N-1} \hat{V}_i^{(2)} \hat{V}_{i+1}^{*(2)} \right] \right\}. \tag{19}$$

This velocity phase $\emptyset_{vel\_T}$ will have a lower Nyquist folding velocity than the velocity phase estimate $\emptyset_{vel}$ but the standard deviation of the velocity phase estimate $\emptyset_{vel\_T}$ will in general be lower than the standard deviation of the velocity phase estimate $\emptyset_{vel}$ for small t_1. Therefore, the velocity phase estimate $\emptyset_{vel}$ can be used to place the velocity phase estimate $\emptyset_{vel\_T}$ in the correct Nyquist interval thereby by giving a velocity phase estimate with a high Nyquist phase and a low standard deviation.

7. To calculate the copolar correlation coefficient, magnitude deconvolution should be applied to the recovered weak signal time series that resulted after step 6 of the phase coding outline in section 1.1 above. After applying magnitude deconvolution to the copolar time series, if needed, the copolar correlation coefficient is calculated as,

$$\rho_{hv} = \left[\frac{\left| \sum_{i=1}^{N} \hat{V}_i^{(1)} \hat{H}_i^{*(1)} \right|}{\sqrt{\sum_{i=1}^{N} \hat{V}_i^{(1)} \hat{V}_i^{*(1)} \sum_{i=1}^{N} \hat{H}_i^{(1)} \hat{H}_i^{*(1)}}} + \frac{\left| \sum_{i=1}^{N} \hat{V}_i^{(2)} \hat{H}_i^{*(2)} \right|}{\sqrt{\sum_{i=1}^{N} \hat{V}_i^{(2)} \hat{V}_i^{*(2)} \sum_{i=1}^{N} \hat{H}_i^{(2)} \hat{H}_i^{*(2)}}} \right] / 2 \tag{20}$$

If the time t_l is small so that there is very small decorrelation between the H_i and V_i

signals, the above estimate of ρ_{hv} in equation 20 can consider the zero lag correlation coefficient

5   between the H_i and V_i time series with very little error.

CLAIMS: